Memorandum

March 28, 2017

To:	Kevin Bilash, USEPA, Region 3	Ref. No.:	11102641
From:	James Moir/kf/3		
cc:	Colleen Costello, David Steele /CC		
Subject:	**CorMix Modeling**		

1. Introduction

The Site was a refinery with oil storage from approximately 1902 until it was idled and ceased operations in September 2012. Currently, the Site is known as the "Marcus Hook Industrial Complex" or "MHIC" and is used for petroleum liquids, ethane, butane and propane storage and gas processing. The Site is located at 100 Green Street, Marcus Hook, PA along the Delaware River. Predominantly, the Site is located on approximately 590 acres along the Delaware River in Marcus Hook, Pennsylvania, but a small portion of the southwest corner of the Site is located in the State of Delaware. GHD has prepared this memorandum to provide Evergreen Resources Group, LLC (Evergreen) with the surface water mixing zone model from the Site to the Delaware River (see Figure 1.1).

The purpose of the surface water mixing zone modeling is to calculate conservative dilution factors for on-Site groundwater discharging to and mixing with surface water (Delaware River) in order to predict the groundwater concentrations that will not result in an exceedance of the DRBC fish ingestion criteria. The acceptable on-Site groundwater concentrations will be calculated by multiplying the dilution factor generated from the modeling results by the applicable Pennsylvania Chapter 93 Surface Water Standards and the Delaware River Basin Commission (DRBC) Surface Water Standards for each groundwater constituent, which can then be compared to available on-Site groundwater results.

2. Mixing Zone Model Software Selection

The first step in the surface water mixing zone modelling study involved determining the most applicable modelling software for the Site-specific groundwater-to-surface water interface. In Pennsylvania, typically the Pennsylvania Department of Environmental Protection (PADEP) PENTOXSD model is utilized for evaluating groundwater discharge to surface water. The application of PENTOXSD to tidally active regions of unconfined aquifers is not described in the PA Act 2 Guidance. The presence of tidal flats along river shorelines can function as areas of groundwater to surface water discharge that may not result in the dilution as would be calculated by PENTOXSD. Based on the *Observations of Tidal Flow in the Delaware River*, E.G. Miller, Geological Survey Water-Supply Paper 1586-C (Paper 1586-C, attached) there is a significant tidal influence along the Site shoreline and as a result CorMix modelling software was utilized instead of PENTOXSD. CorMix is able to more accurately consider mixing behavior and plume geometry under tidal conditions. The CorMix model applies a computational algorithm that considers the mixing zone volume variable dependent on the distance from the original Site-specific groundwater-to-surface water interface. Additionally, CorMix allows for tidal information to be included so that the model can accurately estimate the reduced (conservative) dilution due to tidal re-entrainment.

2.1 CorMix Model Software

Version 9.0 of the CorMix modelling software, distributed by MixZon Inc., was used to calculate the conservative dilution factors for on-Site groundwater discharging to and mixing with surface water in the Delaware River.

2.2 CorMix Input Parameters

Input parameters for the CorMix model include groundwater flux into the receiving surface water body, surface water flux at the point of groundwater discharge, and the dimensions of the receiving surface water body. A summary of the model input parameters and their sources are provided in the text below.

Although CorMix is commonly used as a model used for end-of-pipe mixing, Cormix is also used for modeling seeps along shorelines. To model a seep in CorMix, the approach is to use a "virtual diffuser". The "virtual diffuser" approach used is the multi-port diffuser module with a large number of ports tightly spaced with the ports placed vertically in the water column. This causes CorMix to use the equivalent "slot" calculation (a rectangular shape outlet), thus simulating a seep. The "virtual diffuser" can be any length, also to simulate the seep geometry. The port diameters in the virtual diffuser can be made large so that exit velocities are small, as in a seep.

A conservative approach was taken in selecting parameters describing the dimensions and hydrodynamics of the Delaware River as well as the aquifer and groundwater flow from the Site. The groundwater contours for the area are presented on Figure 1.2. The groundwater gradient into the Delaware River was evaluated across the entire shoreline of the Site, as summarized in Section B.2.3. Based on that evaluation, a conservation flux estimate of 0.02 cubic feet per second (ft^3/sec) was applied along the entire length of the shoreline, even if a bulkhead was present. The entire length of the groundwater-to-surface water interface (shoreline of the Site) was then evaluated by varying the diffuser length in the model.

The individual ports can be defined in CorMix as discharging in either a vertical direction or in a horizontal direction. The outlet ports were positioned in the model in the horizontal direction which is appropriate for discharge with a low flow velocity, as from a zone of groundwater discharge into surface water, since any added momentum in the offshore direction will be negligible.

Based on the examination of the local bathymetry map listed in Paper 1586-C, the local river depth adjacent to the Site was set at 12 ft below the water surface and the local river depth at the diffuser (seep) was set at 9 ft below the water surface and positioned at the shore line. Additionally, the mean ambient receiver velocities (nearshore Delaware River) were based on the tidal discharge and velocity observations (Paper 1586-C) and those average water velocities (2 to 3 ft/sec) were extrapolated to nearshore conditions (Paper 1586-C).

A sensitivity analysis was completed with the CorMix model by running multiple iterations, varying the major input data (port direction and ambient water velocity) to evaluate the sensitivities of the results caused by changes, or assumptions, in the input data. The two most significant variables identified by the sensitivity analysis were the port direction and the ambient (receiver) water velocity. Port direction, in this study, was an approximation of groundwater discharge. The ambient (receiver) water velocity was the only significant variable with physical meaning. A range of steady ambient water velocities and the tidal methodology were used in this CorMix modeling. CorMix has modules for modeling both a constant ambient (receiver) velocity and tidal (oscillating) velocity modules. Both the single velocity and the tidal modules were used in this study. In this study, the tidal methodology gave results essentially identical to "steady-state" (single ambient velocity) modeling at a point in the tidal cycle. The lowest dilutions were calculated for at-slack[1] conditions and highest dilutions were calculated for at-peak (highest velocity) conditions.

The CorMix model considers buoyancy effects based on the relative temperatures of the water in the ambient (Delaware River) and the seep discharge. The ambient river and effluent temperatures were assumed to be the same temperature (53.6°F) and as a result buoyancy effects would not contribute to the results.

2.3 Marcus Hook Site Groundwater Flow and Discharge Calculations

The following presents the method and data used to determine groundwater flow and groundwater discharge from the Site to the Delaware River.

The data were taken from previous reports and existing documentation, as identified below.

Groundwater Flux:

Q = KIA Darcy's Law

Where:

Q = Groundwater flow across Site Shoreline (discharge)

K = Hydraulic conductivity

i = Average groundwater gradient (not including pump location)

A = Cross-sectional area for groundwater flow

Darcy Velocity (Ki):

Hydraulic gradients were calculated between well-pair data from the July 2015 Stantec Current Conditions Report (Stantec 2015). The average value presented below excludes well locations in immediate proximity to pumping wells. Gradient values were calculated based on the water level elevations presented in Table 1. Hydraulic conductivity values were calculated based on single-well response tests presented below:

1 "Slack" tide is the point in the tidal cycle where the tide is changing direction. At slack the water velocity is zero. There is a point in the tidal cycle where the water velocities are at a maximum, "at peak".

Well	ft/d	cm/s
MW-532	0.4753	1.67E-04
MW-36	0.4931	1.74E-04
MW-320	0.3073	1.08E-04
MW-214	0.1238	4.37E-05

A range of Darcy velocity values were calculated based on the above values and the gradients from Table 1.

	k*I (ft/d)	k*I (ft/sec)
Minimum	0.0005	5.3E-09
Maximum	0.0112	1.3E-07
Mean	0.0033	3.9E-08
Geomean	0.0018	2.1E-08

Cross-Sectional Area (A):

A = DW

Where:

A = Cross-Sectional Area

D = Average Depth of Saturated Aquifer

W = Width of Site along shoreline based on linear length from SW corner of AOI-7 to SE corner of AOI-3

Depth:

Based on groundwater elevations measured in September, 2015

Well	D (ft)
MW-532	13.3
MW-531	27.62
MW-530	20.48
MW-529	28.57
MW-528	22.86
MW-527	23.62
Ave. Depth	**22.74**

Width:

W 4,987 ft

Average Area:

A = DW 113,404 ft

Groundwater Discharge to the Delaware River:

$Q = KiA$

$Q_{min} =$ 0.00060 (ft^3/sec)

$Q_{max} =$ 0.01468 (ft^3/sec)

$Q_{mean} =$ 0.00437 (ft^3/sec)

$Q_{geomean} =$ 0.00236 (ft^3/sec)

Selection of Groundwater Discharge Rate:

Hydraulic conductivity data are log-normally distributed, so a geometric mean may be considered appropriate. However, as noted above, the hydraulic conductivity values are based on single well response tests (slug testing), which can underestimate hydraulic conductivity compared to longer duration multiple well aquifer tests, sometimes up to an order of magnitude. Therefore, the Qmax was used, and rounded up to 0.02 ft^3/sec to provide a sufficiently conservative estimate for the mixing factor calculation.

An alternative modeling approach to evaluate the shoreline for the Site is to assume a single very long multiport diffuser, with lengths from 160 ft up to 1,000 ft. The port density was maintained at 2 ports per meter length. All other diffuser model settings were kept the same as before. The ports were placed at the water surface and simulations run at port diameters of 0.8 to 2.5 cm.

The only input data that was varied in the model was diffuser length and river currents. Diffuser lengths of 164 ft, 328 ft, 492 ft, 656 ft and 984 ft and ambient current velocities of 0.003 ft/sec, 0.03 ft/sec, 0.5 ft/sec and 1.0 ft/sec were used in the model.

2.4 CorMix Results

Figures 2.1, 2.2, and 2.3 present the CorMix results. Figure 2.1 presents all the calculated mixing factors, at the distance from the seep where the dilution factor begins to exceed 10,000; this is also the distance point at which passive ambient dilution[2] begins. At this point, dilution rapidly increases over a distance of about 3 ft to 4 ft, increasing from about 8 to about 10,000 as the plume rapidly spreads. For these "long diffuser" geometries CorMix provides output on either side of this transition.

Figure 2.1 presents three points with relatively low dilution factors. These three values were for a "slack tide" (near zero ambient river current velocity).

Figure 2.2 presents the effect of modeled diffuser length; all five modeled lengths provide similar dilution factors. This suggests that diffuser length is not a significant variable in estimating dilution factor.

Figure 2.3 shows the effect of ambient river current velocity on predicted dilution factors. If ambient river current velocity exceeds 6 in/sec, then the predicted dilution factor is at or exceeds 10,000. At the short period of slack tide, where ambient river current velocity is 0.033 ft/sec or less, and within 1,000 ft to 1,300 ft of the seep center, the predicted dilution factor is less than 10,000. At dead slack tide at the seep, the

[2] CorMix module 261.

dilution factor may be as low as 60 but this is only expected to last a few minutes each tide cycle, but as the tide turns will rapidly rise back up to 10,000.

3. Recommendations

Based on the surface water mixing zone model results, GHD recommends a conservative dilution factor of 10,000 be applied to the Delaware River Basin Commission (DRBC) Surface Water Critiera to back calculate corrective action objectives for Site groundwater.

Figures

Source: NAIP IMAGERY OF DELAWARE, 2015 - U.S. DEPARTMENT OF AGRICULTURE (USDA) FARM SERVICE AGENCEY, AERIAL PHOTOGRAPHY FIELD OFFICE.

0 550 1100ft

Coordinate System:
PENNSYLVANIA SOUTH
NAD83 FEET

PROJECT NORTH

LEGEND

PROPERTY BOUNDARY ALONG THE DELAWARE RIVER

SUNOCO MARCUS HOOK
MARCUS HOOK, PENNSYLVANIA
MARCUS HOOK INDUSTRIAL COMPLEX

SITE LOCATION

11102641-00

Apr 6, 2016

FIGURE 1.1

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Source: Microsoft Product Screen Shot(s) Reprinted with permission from Microsoft Corporation, Acquisition Date: Aug-Sept 2014, Accessed: 2016.

0 400 800ft

Coordinate System:
PENNSYLVANIA SOUTH
NAD83

N

GHD

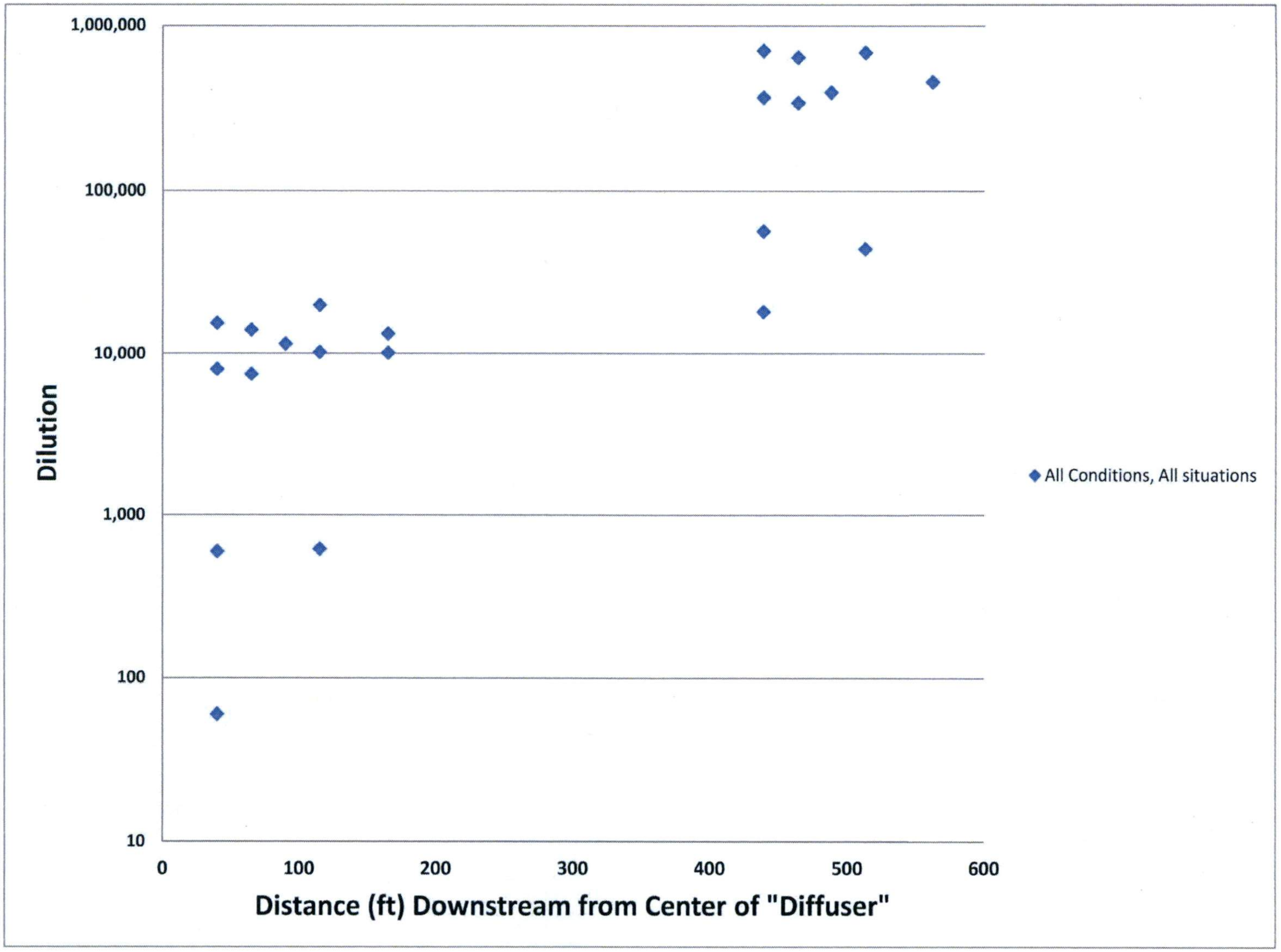
SUNOCO MARCUS HOOK
INDUSTRIAL COMPLEX
MARCUS HOOK, PENNSYLVANIA

GROUNDWATER CONTOURS
OCTOBER 2015

11102524-03
Apr 5, 2016

FIGURE 1.2

CAD File: P:\drawings\11100000s\11102524\11102524-reports\11102524-03(003)\11102524-03(003)GN\11102524-03(003)GN-WA002.DWG



SUNOCO MARCUS HOOK
MARCUS HOOK, PENNSYLVANIA
MARCUS HOOK INDUSTRIAL COMPLEX

CORMIX MIXING MODEL - "LONG DIFFUSER"
DILUTION VS. DISTANCE FROM DIFFUSER

11102641-00

Apr 6, 2016

FIGURE 2.1

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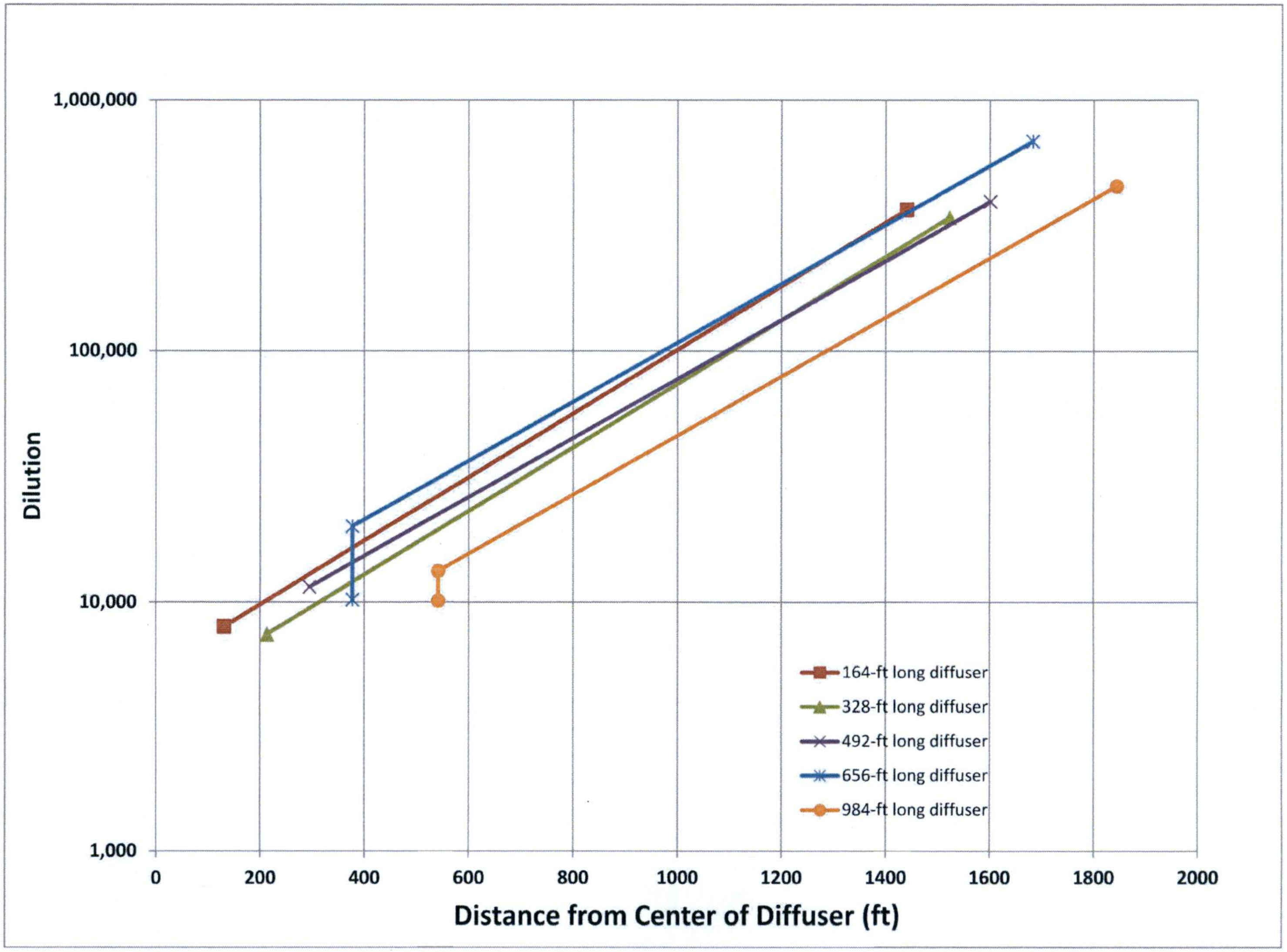

SUNOCO MARCUS HOOK
MARCUS HOOK, PENNSYLVANIA
MARCUS HOOK INDUSTRIAL COMPLEX

CORMIX MIXING MODEL - EFFECT OF DIFFUSER LENGTH
("LONG DIFFUSER" DILUTION VS. DISTANCE FROM DIFFUSER) FIGURE 2.2

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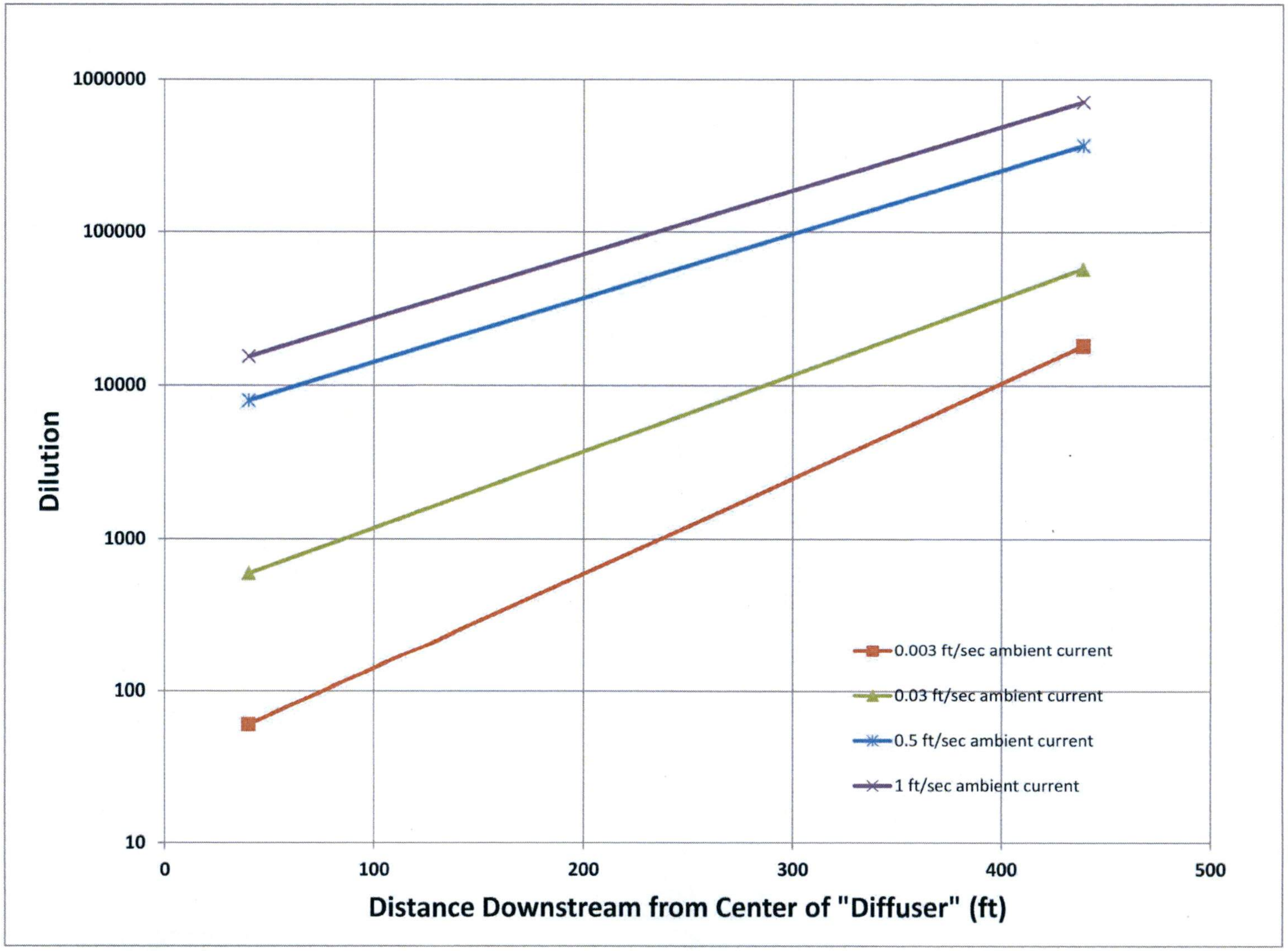

SUNOCO MARCUS HOOK
MARCUS HOOK, PENNSYLVANIA
MARCUS HOOK INDUSTRIAL COMPLEX

CORMIX MIXING MODEL -EFFECT OF AMBIENT CURRENT (STATE TIDE)
("LONG DIFFUSER" DILUTION VS. DISTANCE FROM DIFFUSER) FIGURE 2.3

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Apr 6, 2016

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Table

Table 1

Marcus Hook - Gradients Between Well Pairs
Marcus Hook, Pennsylvania

AOI	Well	Elevation	Distance from Upgradient Well	Gradient (ft/ft)	K (ft/d)	k*I (ft/d)	k*I (ft/sec)
3	MW-499	2.82					
	MW-500	2.37	229	0.0020	0.4931	0.0010	1.1E-08
	MW-26	1.97	235	0.0017	0.4931	0.0008	9.7E-09
	MW-28	1.48	218	0.0022	0.4931	0.0011	1.3E-08
	MW-97	1.85					
	MW-127	1.73	129	0.0009	0.4931	0.0005	5.3E-09
	MW-489	4.15					
	MW-30	1.27	127	0.0227	0.4931	0.011	1.3E-07
6	MW-320	7.1					
	MW-35	1.2	184	0.032	0.1238	0.004	4.6E-08
	MW-37	-0.3	151	0.0099			
	MW-321	4.92					
	MW-176	2.99	286	0.0067	0.1238	0.001	9.7E-09
	MW-321	4.92					
	MW-79	2.98	337	0.0058	0.1238	0.001	8.2E-09
5	MW-325	6.74					
	MW-141	1.95	156	0.0307	0.3073	0.0094	1.1E-07
	MW-40	5.33					
	MW-324	0.13	262	0.0198	0.3073	0.0061	7.1E-08
7	MW-57	4.12					
	MW-58	2.24	903	0.0021	0.4753	0.0010	1.1E-08
			Minimum:	0.0009		0.0005	5.3E-09
			Maximum:	0.0321		0.0112	1.3E-07
			Average:	0.0114		0.0033	3.9E-08
			Stdev.:	0.0117		0.0039	4.5E-08
			Geomean:	0.0061		0.0018	2.1E-08

Attachment

Observations of Tidal Flow in the Delaware River

By E. G. MILLER

HYDROLOGY OF TIDAL STREAMS

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1586-C

Prepared in cooperation with the Corps of Engineers, Department of the Army, and the New Jersey Department of Conservation and Economic Development

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

[illegible]
in the Delaware River

[illegible]

[illegible]

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

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HYDROLOGY OF TIDAL STREAMS

OBSERVATIONS OF TIDAL FLOW IN THE DELAWARE RIVER

By E. G. MILLER

ABSTRACT

The investigation described in this report was made at the Burlington-Bristol Bridge and the Delaware Memorial Bridge, in the tidal reach of the Delaware River below Trenton, N.J. Continuous measurements of depth and velocity through complete tidal cycles were made by 5 crews working simultaneously on 5 days in August between 1955 and 1957. From these data it was possible to compute the instantaneous upstream or downstream flow for any selected time during the measurements.

Maximum rates of tidal flow in the Delaware River proved to be very large, as compared with the fresh-water flow entering the tidal reach. On the day of a measurement at the Delaware Memorial Bridge, the maximum downstream rate of flow was almost 400,000 cfs and the maximum upstream rate was almost 600,000 cfs, as compared with the daily mean discharge of 1,650 cfs at Trenton on that day. Apparently, reliable figures of net downstream flow cannot be obtained by subtracting the total upstream flow from the total downstream flow and correcting for changes in storage. Hence, this procedure cannot be used satisfactorily to detect ground-water inflow.

This report shows that satisfactory correlation might be obtained between velocity at a fixed point in a cross section of the river and the mean velocity in that cross section. Thus, with a continuous record of velocity obtained by a recording current meter at a fixed point and a continuous record of stage obtained by a water-stage recorder, it would be possible to estimate the instantaneous upstream or downstream flow of the river at any time.

Observations of specific conductance at Burlington-Bristol Bridge showed no significant variation during the tidal cycles studied, but at the Delaware Memorial Bridge the variation was pronounced, showing an increase in specific conductance when the tide came in and a decrease when the tide went out. This variation in specific conductance was a measure of the salinity caused by the movement of ocean water upstream.

INTRODUCTION

During recent years, interstate negotiations for development of the Delaware River and the rapid growth of population and industry along the tidal reach of the river have created new problems and a demand for information about the flow characteristics in the tide-affected reach below Trenton, N.J. Except for depths and surface velocities in navigable channels, little is known about the characteristics of tidal reaches. The information contained in this report is intended as a step toward defining the characteristics of tidal streams in general and those of the Delaware River in particular, and to help point the way toward future investigations.

PURPOSE AND SCOPE

To investigate some of the flow characteristics in the tidal waters of the Delaware River, a study was started in August 1955 with the following specific objectives:

1. Compute the amount of upstream and downstream flow for the selected tide cycles.
2. Investigate the possibility of using the described procedure to compute net downstream discharge and to detect ground-water inflow.
3. Determine the feasibility of relating flow to some index velocity and a record of stage.
4. Relate the variations in specific conductance to the changes in stage and velocity.
5. Acquire new knowledge of tidal-flow phenomena for use in future investigations of tidal streams.

ACKNOWLEDGMENTS

This report was prepared by the U.S. Geological Survey in cooperation with the Philadelphia District, Corps of Engineers, U.S. Army, and the New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply. The investigation was planned and started in 1955 by O. W. Hartwell, district engineer, and N. H. Beamer, district chemist, U.S. Geological Survey. All observations of specific conductance and pertinent computations were made under the direction of Mr. Beamer. Flow measurements in 1955 and 1956 were made under the direction of Mr. Hartwell, and the one in 1957 under the direction of D. F. Dougherty, district engineer (November 1956 to September 1958). Since September 1958 the project has been directed by J. E. McCall, district engineer. The fieldwork was supervised by G. S. Hayes, hydraulic engineer, prior to February 1956, and by A. C. Lendo, hydraulic engineer, thereafter.

Acknowledgment is given to J. M. Ludlow, R. T. Mycyk, and M. A. Walker for performing the laborious computations of tidal flow, and to engineers of the Equipment Development Laboratory, Columbus, Ohio, for assistance in adapting stream-gaging equipment to the special needs of the investigation.

COLLECTION OF FIELD DATA

Continuous observations of stage and velocity throughout a full tidal cycle were made on each of 4 days from the Burlington-Bristol Bridge, N.J.–Pa., and on 1 day from the Delaware Memorial Bridge, N.J.–Del., as tabulated below:

Location	Date	Mean discharge at Trenton (cfs)
Burlington-Bristol Bridge, N.J.–Pa.	Aug. 9, 1955	2,480
Do.	Aug. 16, 1956	3,860
Do.	Aug. 17, 1956	3,680
Do.	Aug. 24, 1956	4,000
Delaware Memorial Bridge, N.J.–Del.	Aug. 21, 1957	1,650

The sites of the investigations are shown on figure 1. All five of the tidal-cycle measurements were made at times when the fresh-water discharge at Trenton was comparatively low, as shown by the fact that the mean discharge of the Delaware River at Trenton on the days of the measurements was considerably below the average discharge of 11,790 cfs (cubic feet per second) for the 44 years ending September 1957. The minimum discharge of the Deleware River at Trenton during those 44 years was 1,220 cfs on September 18 and 19, 1932.

On all 5 days that tidal-cycle measurements were made, daylight hours were utilized to the fullest extent possible. Dates were selected so that either high tide or low tide occurred shortly after sunrise. Observations were made from this time of high or low tide until the similar tide returned shortly before sunset.

INDEX CURRENT METER

Observations of depths and velocities of the tidal flow were made from the bridges by using 75-pound sounding weights and Price current meters. A key element of all the tidal-cycle measurements was the operation of an index current meter near the center of the main channel at each bridge. These meters were maintained at 0.6 of the depth below the surface, although occasionally check observations were made at 0.2 and 0.8 of the depth below the surface. During the first tidal-cycle measurement, observations by the index velocity meter were made every 15 minutes, but changes of velocity were so rapid and surges and pulsations of flow so extensive that these observations were not frequent enough to define velocity changes with satisfactory accuracy. During all subsequent measurements, readings of velocity at the index meter were made every 5 minutes except dur-

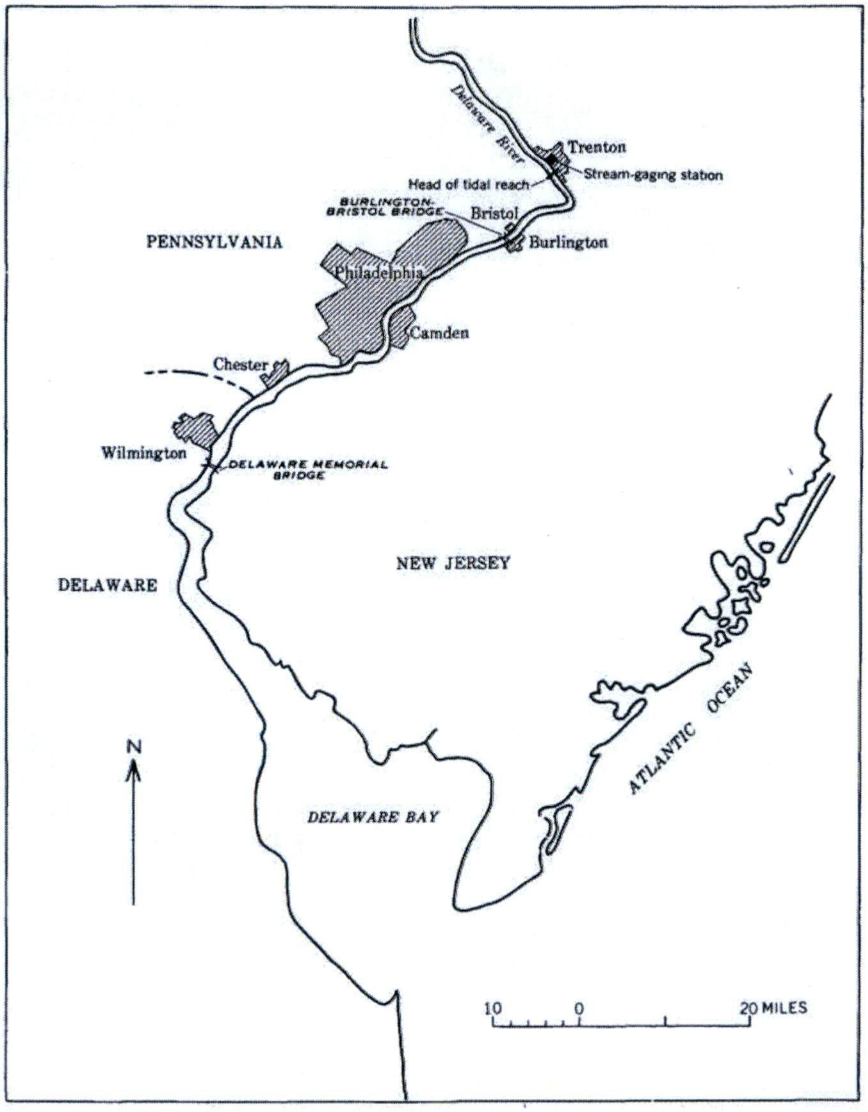

FIGURE 1.—Map showing tidal reach of the Delaware River.

ing slack water when readings were made continuously. This procedure gave adequate definition although there was considerable scattering of the individual observations. Figure 2 shows a typical example of the extent of this scattering and the mean curve that was drawn through the points.

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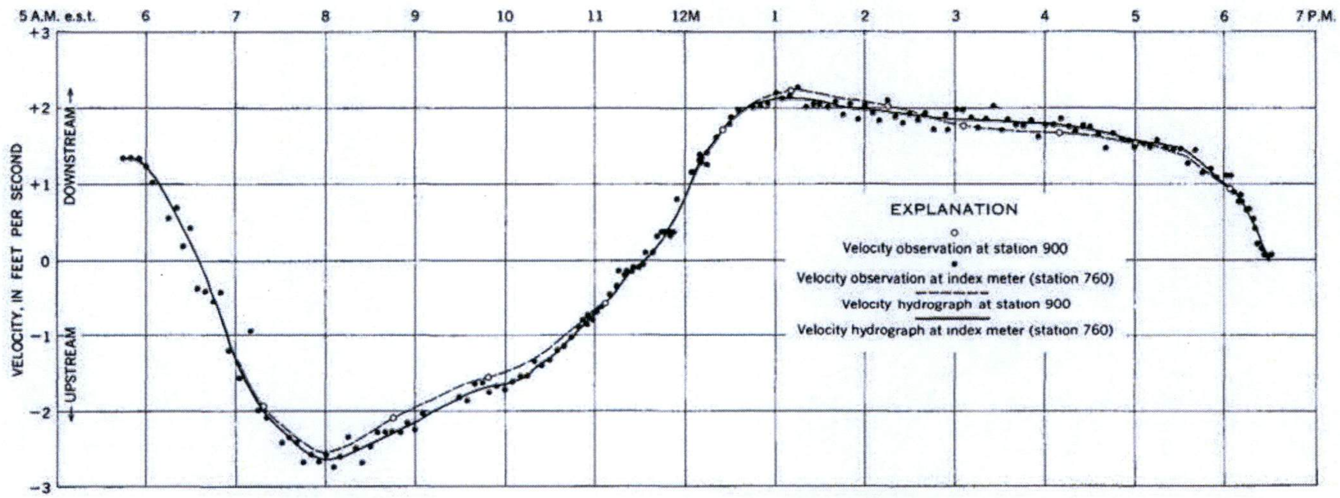

Figure 2.—Velocity hydrographs at index meter and at station 900 on Delaware River at Burlington-Bristol Bridge, August 16, 1956.

ADDITIONAL OBSERVATIONS

In addition to the velocity observations made at the index meter, numerous determinations of depth and velocity were made throughout each day of the tidal-cycle measurements. Four stream-gaging crews made systematic observations at designated stations across the entire cross section. Each crew covered approximately one-fourth the width of the river and repeated its series of observations as soon as one series was completed. This routine was continued throughout the day of each measurement.

SOUNDINGS

Soundings of the depth of water at each station were made concurrently with velocity observations, and a record of river stage was obtained by a temporary water-stage recorder installed on the crib work near one of the main piers. Each sounding was adjusted for the stage at the time of observation to give a depth of water referred to zero gage height at the temporary gage. All adjusted depths were averaged for each station for each tidal-cycle measurement, and standard cross sections were drawn, as shown in figures 3 and 4. At the Burlington-Bristol Bridge, repeated observations were made at 32 stations and single observations at 22 additional stations. At the Delaware Memorial Bridge repeated observations were made at 34 stations and single observations at 11 additional stations. A considerable change in the cross section at the Burlington-Bristol Bridge was caused by scour during the flood following hurricane Diane, August 20, 1955, as can be seen in figure 3.

DETERMINATION OF MEAN VELOCITY

The mean velocities at all stations in the cross section, other than those at the index meter, were determined by averaging the observations at 0.2 and 0.8 of the depth below the surface. To test the validity of the two-point (0.2 and 0.8) method, vertical velocity curves were obtained for two stations in the cross section at the Burlington-Bristol Bridge (fig. 5). These curves were based on velocities obtained at 5-foot vertical intervals on August 23, 1956, when the direction of flow was upstream. The shapes of the resulting curves are typical of vertical-velocity curves for comparatively deep, sluggish streams. At these two stations, the mean velocities obtained by the two-point method agreed within a few percent with the mean velocities obtained by integrating the vertical-velocity curves, which demonstrates the validity of the two-point method at the Burlington-Bristol Bridge cross section. Although no vertical-velocity curves were obtained at the Delaware Memorial Bridge, it is believed that this bridge also is

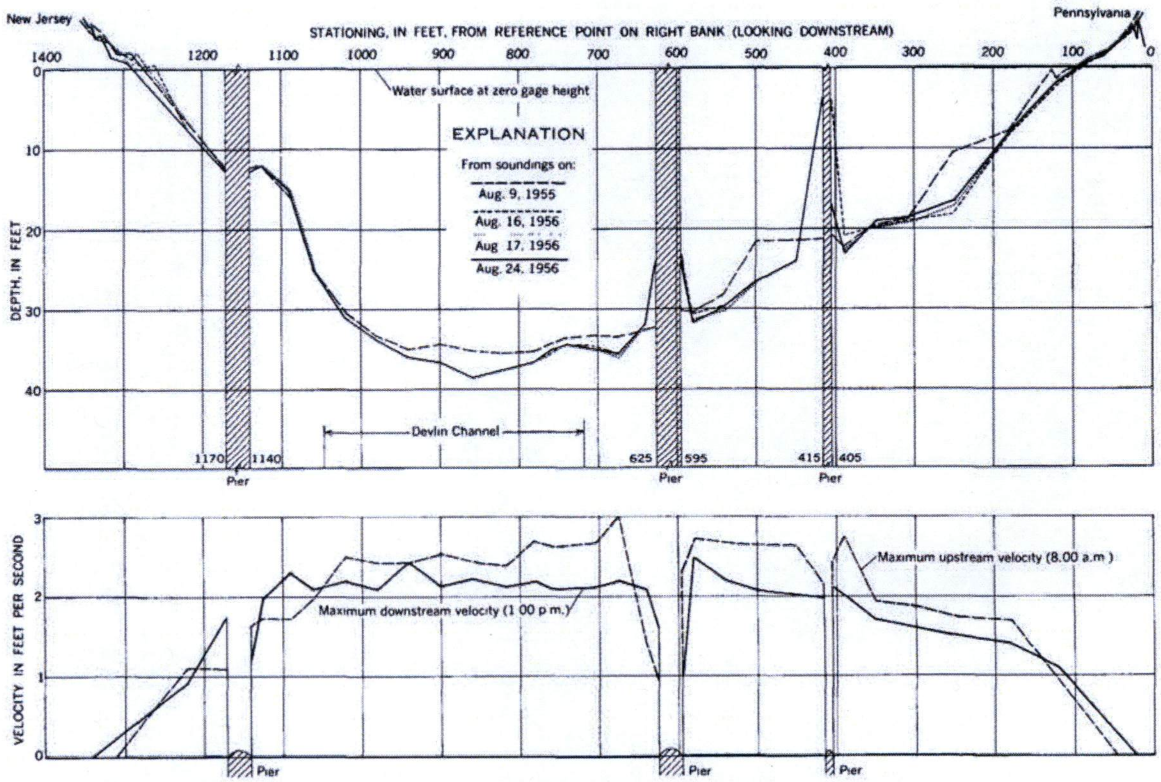

FIGURE 3.—Cross section of Delaware River at Burlington-Bristol Bridge, and variation of maximum velocity, August 16, 1956.

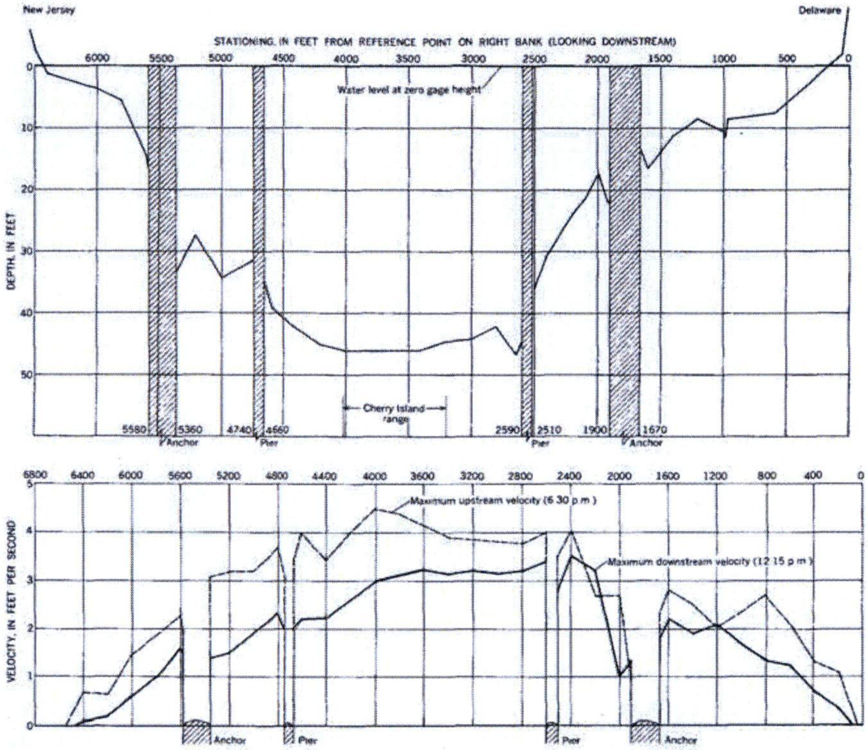

FIGURE 4.—Cross section of Delaware River at Delaware Memorial Bridge, and variation of maximum velocity, August 21, 1957.

far enough upstream from the entrance to the bay so that the two-point method of determining mean velocity is valid.

ANALYSES OF DATA

VELOCITY VARIATIONS

A velocity hydrograph at each designated station of the cross section throughout each tidal-cycle measurement was drawn on the basis of velocity observations at each station, with consideration being given to the shape of the velocity hydrograph at the index meter for the same day. An example of a velocity hydrograph is shown in figure 2. This figure shows the 11 velocity observations made at station 900 of the Burlington-Bristol Bridge on August 16, 1956, plotted on the same sheet and to the same scales as the velocity hydrograph at the index meter located at station 760. The dashed line was drawn through the points of the velocity observations at station 900 with interpolation between points based on the shape of the velocity hydrograph for the in-

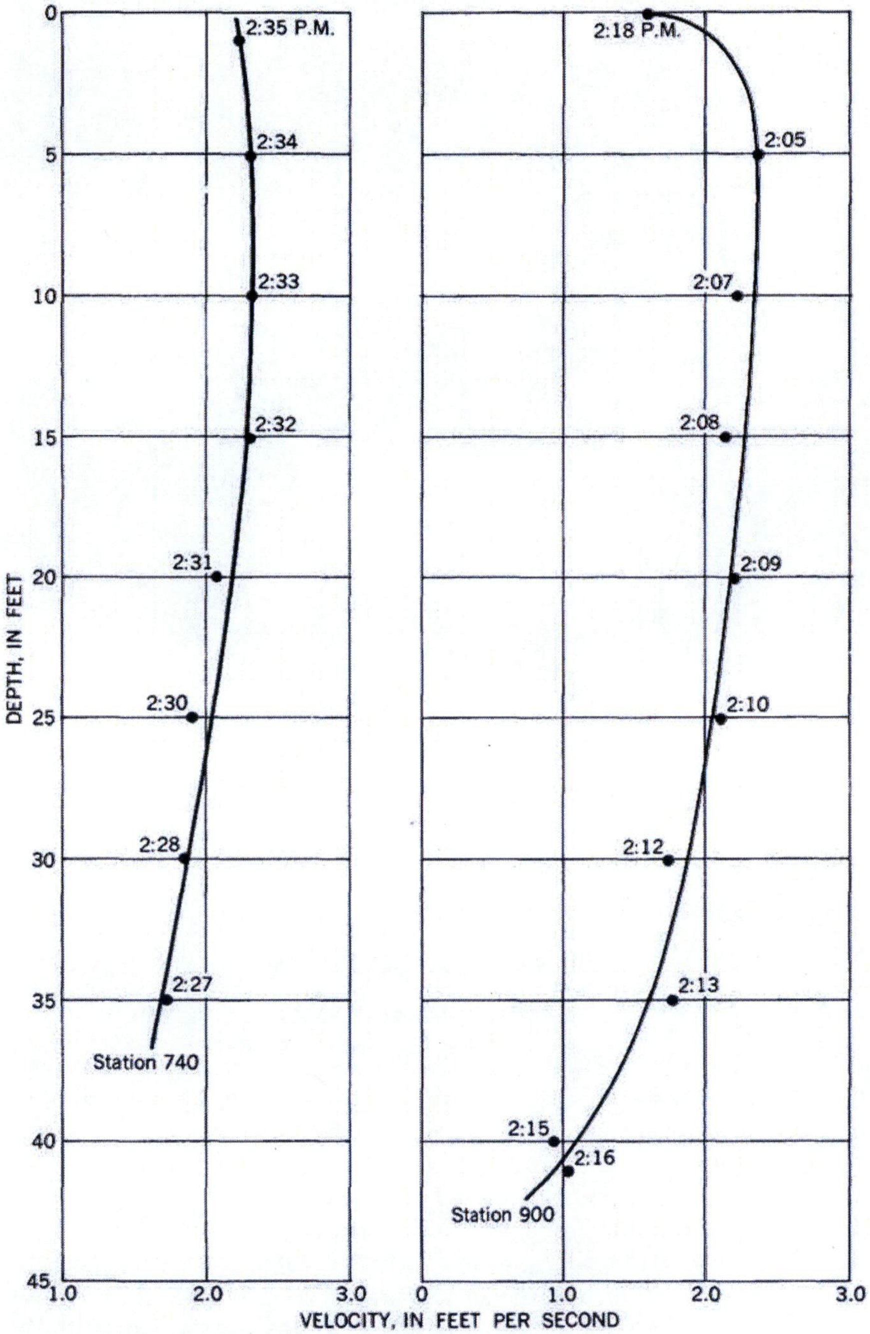

FIGURE 5.—Vertical-velocity curves of Delaware River at Burlington-Bristol Bridge, August 23, 1956.

dex meter. At some stations, as many as 15 observations were made in the course of a day. At almost all the stations four or more observations were made except at those on the tidal flats where there was no water at low tide.

Figure 2 shows that the velocity hydrograph, as drawn for station 900 of the Burlington-Bristol Bridge on August 16, 1956, differs little from the velocity hydrograph for the index meter.

Although figures showing the rate of flow are tabulated in this report for all four measurements made at the Burlington-Bristol Bridge, only the hydrographs for the measurement made on August 16, 1956, are shown. The hydrographs for the other three measurements are available for inspection at the Trenton district office of the U.S. Geological Survey.

The velocity hydrographs made it possible to determine the velocity at any designated station for any time during the measurements. Information from these curves was used to draw the parts of figures 3 and 4 which show the velocity variation across the Delaware River at the times of maximum upstream and downstream velocity at the Burlington-Bristol Bridge on August 16, 1956, and at the Delaware Memorial Bridge on August 21, 1957. Similar plots could be made for any specific time during the days of measurement.

GAGE-HEIGHT VARIATIONS

The gage-height hydrographs indicating the variations of the water level during the tidal cycles at the Burlington-Bristol Bridge on August 16, 1956, and at the Delaware Memorial Bridge on August 21, 1957, are shown in figures 6 and 7. These records of stage were obtained from the temporary water-stage recorders. The variations of velocity at the index meter for the same two measurements are also shown in figures 6 and 7. This combination of stage and velocity hydrographs on the same sheet presents a good picture of the behavior of flow during the particular tidal cycles shown.

FLOW COMPUTATIONS

With depths and velocities available for all stations and times during the tidal-cycle measurements, it was a simple procedure to compute the flow for any instant. The depth of water was obtained by adding the gage height for the particular time to the depth obtained from the standard cross section for zero gage height, and the velocity was obtained from the velocity hydrograph. Then the flow was computed by summing the products of areas and velocities for the subsections of the channels. This method of computing the flow utilized values of depths and velocities that occurred from one shore to the

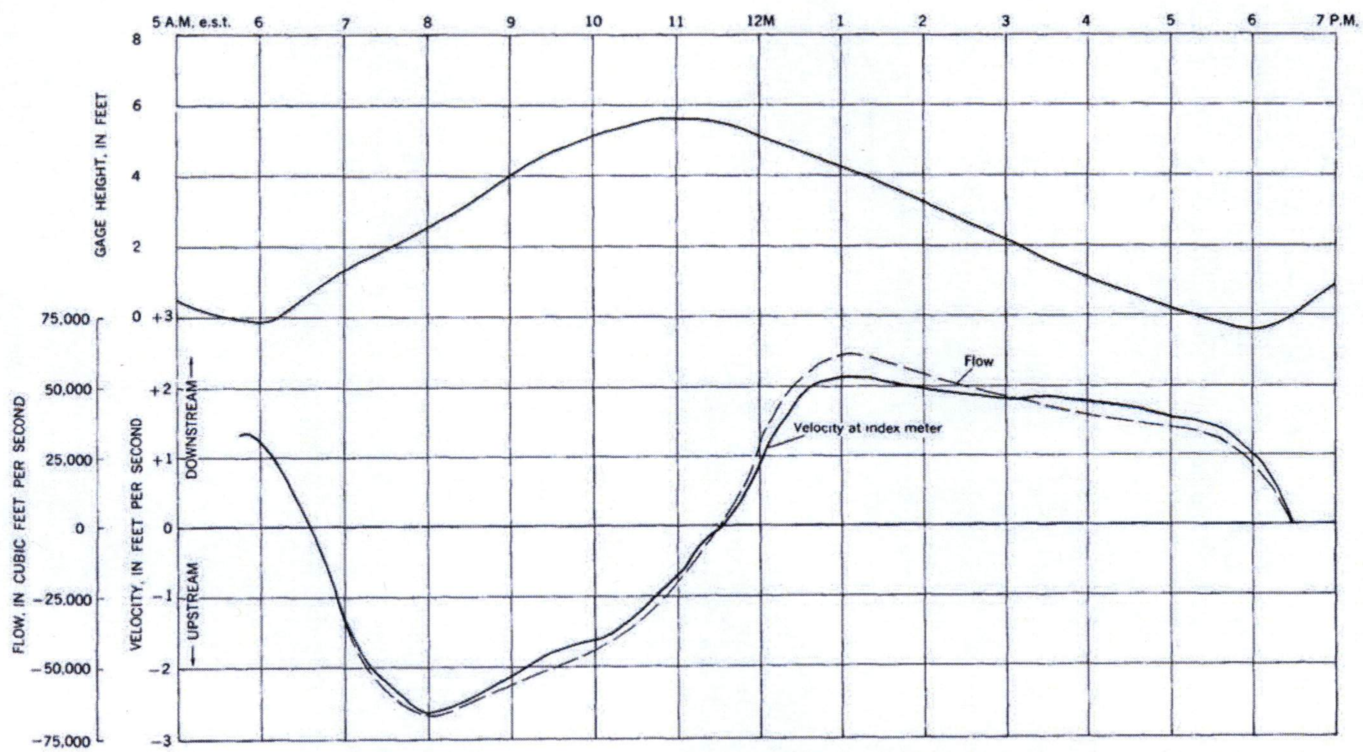

FIGURE 6.—Gage height, velocity, and flow hydrographs of Delaware River at Burlington-Bristol Bridge, August 16, 1956.

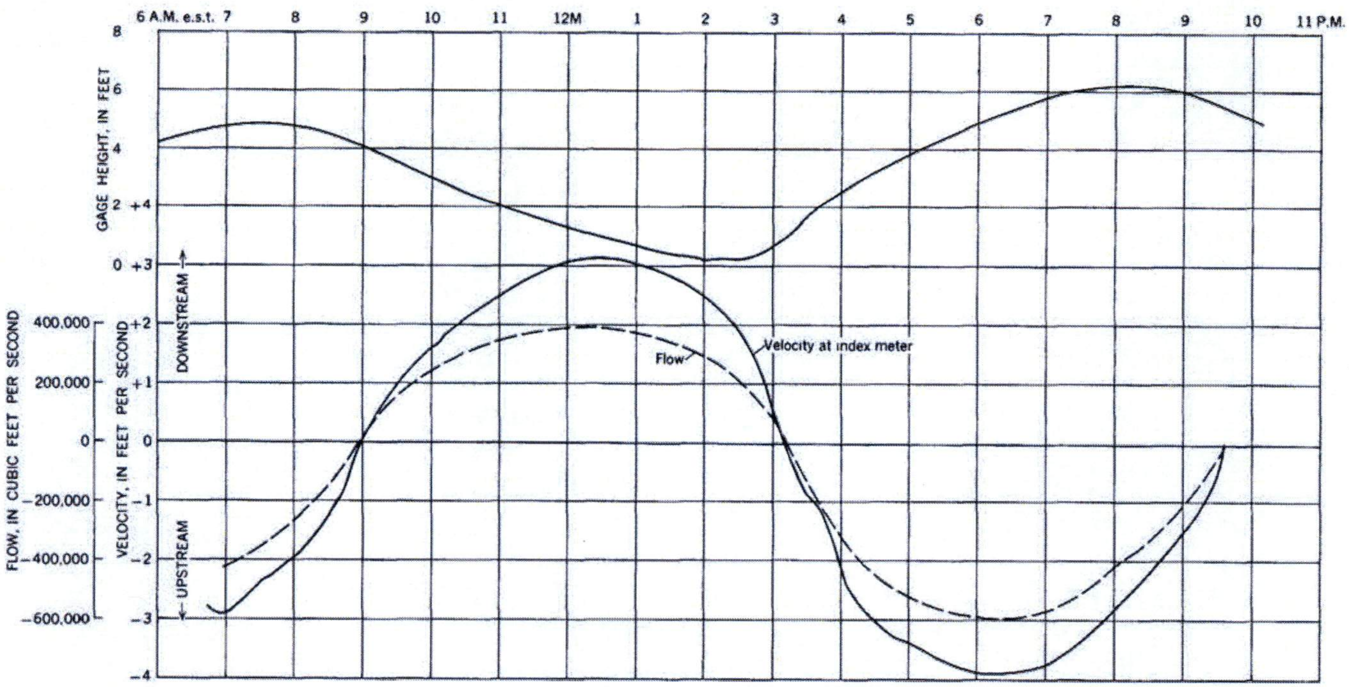

Figure 7.—Gage height, velocity, and flow hydrographs of Delaware River at Delaware Memorial Bridge, August 21, 1957.

other at the particular moment desired, and thus overcame the problem of rapidly changing stage and velocity. The flow was computed for each hour and the computed values were plotted and connected by a smooth line. The flow hydrographs at the Burlington-Bristol Bridge on August 16, 1956, and at the Delaware Memorial Bridge on August 21, 1957, are shown on figures 6 and 7 along with the gage-height and index-velocity hydrographs. The computed values of flow for all the measurements are tabulated in table 1.

To compute the volume of water flowing in each direction between times of slack water, the areas under the flow hydrographs were planimetered, and the resulting areas were converted to cubic feet. These totals, shown in table 1, indicate for each day of the measurements the total volumes of upstream flow past the bridge during flood tide and downstream flow past the bridge during ebb tide. The difference between these two volumes is a measure of the net flow downstream during the tidal cycle. However, the net flow is a comparatively small difference between two large numbers, and the errors in the large numbers would be greatly magnified in the difference. For example, at the Burlington-Bristol Bridge on August 16, 1956, changing the computed values of upstream and downstream flow by 5 percent could change the difference by 34 percent. Furthermore, a correction would have to be made for change in storage, because the gage-height or tide level at the end of the measurements was never the same as at the beginning. This change in storage was substantial in most of the tidal cycles observed during the investigation. There are more than 5 square miles of water surface between the Burlington-Bristol Bridge and the head of tide at Trenton and more than 50 square miles of water surface between the Delaware Memorial Bridge and Trenton. Thus, the complications in attempting to compute accurate corrections for tidal storage over such large water areas, mud flats, and swamps, are obvious. Considering the effect of these two sources of error, it appears that reliable figures of net downstream flow cannot be obtained by subtracting the total upstream flow from the total downstream flow and correcting for changes in storage.

WATER TRAVEL

An estimate of water travel can be obtained from velocity hydrographs such as those shown in figures 6 and 7. The areas under the velocity curves for the index meter between times of slack water were planimetered, and the resulting areas were converted to distance, in feet, of water travel. The distances obtained by this procedure are listed in table 1. They represent the length of a filament of water passing the index meter and not necessarily the distance traveled by any given particle of water. The actual travel of water during a flood tide or an ebb tide is affected by changes in cross-sectional area upstream or downstream from the measured cross section. If the channel were uniform in cross section and if the distances tabulated in table 1 were multiplied by a factor to adjust the velocity at the index meter to the mean velocity of the river, the mean water travel during a tidal cycle could be obtained. The channel, however, has no abrupt contractions in cross section for several miles upstream or downstream from the two bridges. Therefore, as the index meter was near the point of maximum velocity in the cross section, the length of the filament passing the index meter represents fairly closely the maximum distance any one particle of water could travel during that tidal cycle.

VELOCITY RELATIONS

Correlation curves were drawn to check the relationship between the velocity at the index meter and the mean velocity in the river. The mean velocity in the river at each hour of the tidal-cycle measurements was determined from the hourly discharge measurements that had been computed previously, and the velocity at the index meter for the same times was obtained from the velocity hydrograph at the index meter. Figure 8 shows the plotting of all these hourly data for the four tidal-cycle measurements at the Burlington-Bristol Bridge. The relation curve is a well-defined straight line passing through the origin with a slope of 0.90, indicating that at all times the mean velocity in the river was about 0.90 that of the index velocity. So long as this relation holds, the only base data required for computing the flow of the river at this location for any instant are the gage height and a velocity reading at the index position.

Other points in the cross section away from the main river traffic might be used for the location of a flowmeter in case further studies or a continuous record are desired. Station 415, located near a pier, was selected as a location where a permanent flowmeter might be installed; and a curve was drawn to check the relation between the velocity at station 415 and the mean velocity in the river. This curve (fig. 9), constructed in a manner similar to that used for constructing the relation curve for the index meter location is a straight line passing through the origin with a slope of 1.05, indicating that the mean velocity in the river was about 1.05 times that at station 415. No other sites for locating a flowmeter were investigated, but it is possible that other suitable locations with good correlations could be found.

The curve in figure 9 shows the relation between the mean velocity at station 415 and the mean velocity in the river. The velocity observations at station 415 were taken at 0.2 and 0.8 of the depth below the

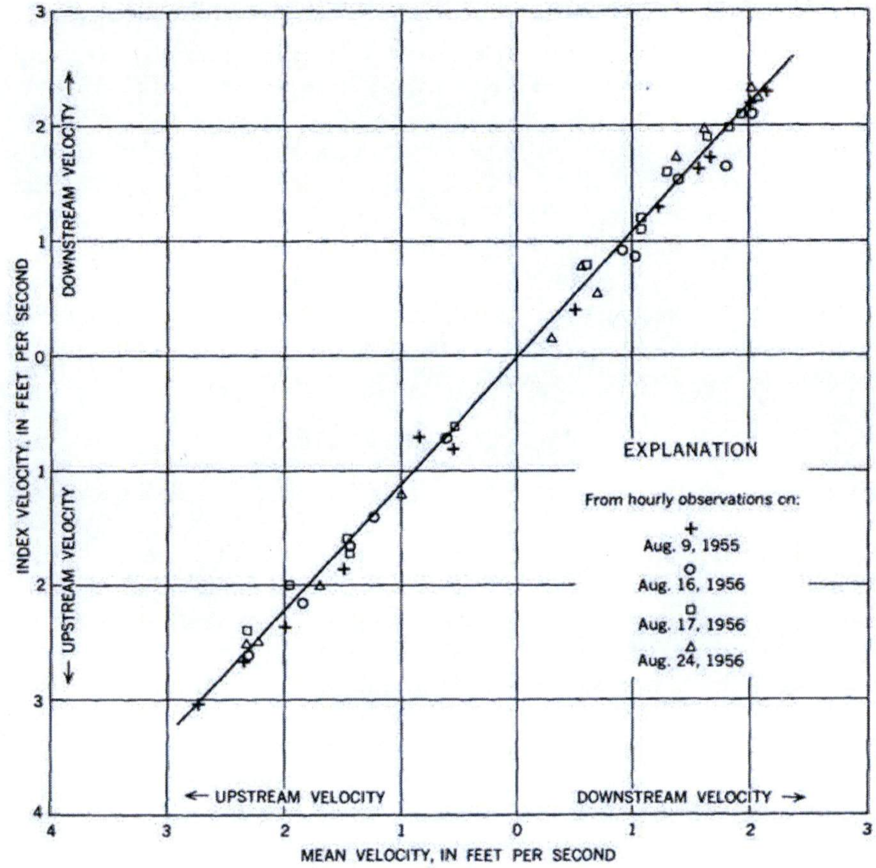

FIGURE 8.—Relation of mean velocity and velocity at index station of Delaware River at Burlington-Bristol Bridge.

surface, but it is assumed that velocity observations at a fixed percentage of the depth below the surface would have correlated with the mean velocity in the river equally well. If a permanent flowmeter were ever installed in the river, however, it probably would be located at a fixed elevation. As the depth of the water varied, the percentage of the depth that the fixed flowmeter was below the surface would also vary. Therefore, before any flowmeter is installed at a fixed position, it must be established that the velocity at the fixed position correlates well enough with the mean velocity at the station that the fact that the depth of the water changes with tide may be disregarded. Also, if the meter is installed at some station other than station 415, the relation between the mean velocity at that station and the mean velocity in the river should be established.

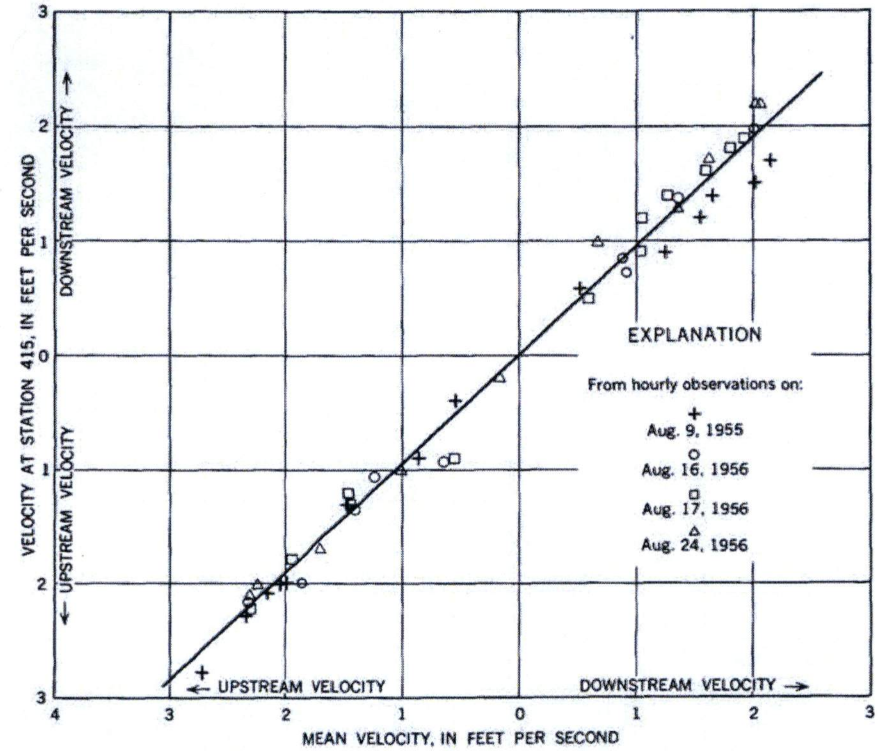

FIGURE 9.—Relation of mean velocity and velocity at station 415 of Delaware River at Burlington-Bristol Bridge.

Although the observations at the Delaware Memorial Bridge were made for only 1 day, the relation of the velocity at the index meter with the mean velocity in the river, as shown in figure 10, appears to be satisfactory. It is drawn as a straight line passing through the origin with the mean velocity in the river 0.87 times that of the index velocity. Two other sites away from the main river traffic were investigated as possible locations for an index meter in case further studies or a continuous record were desired. Figures 11 and 12 show the relation curves of the mean velocity in the river with the velocity at stations 2600 and 4800 respectively. Both are drawn as straight lines passing through the origin with the mean velocity in the river 0.80 and 1.07 times that of the selected station velocity, respectively. Since the number of observations at each of these points is small, additional data should be obtained before a site is chosen for a permanent flowmeter at the Delaware Memorial Bridge.

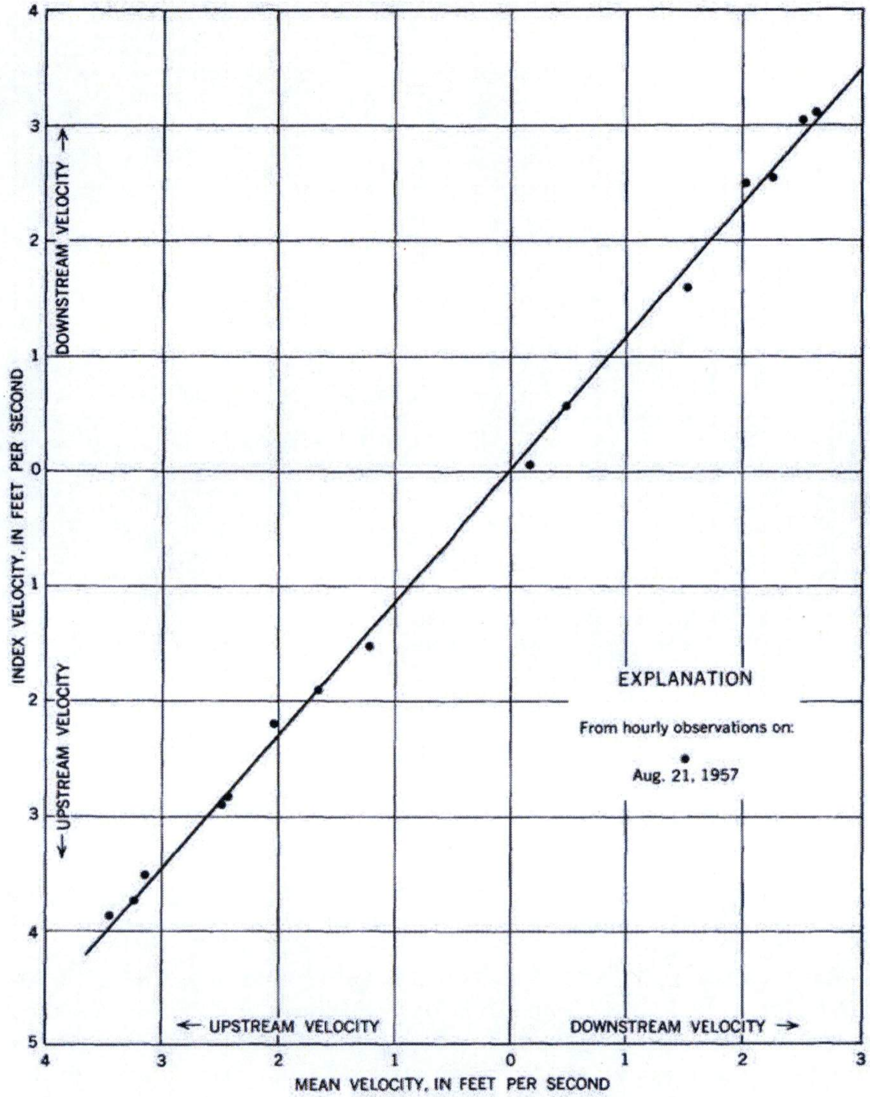

FIGURE 10.—Relation of mean velocity and velocity at index station of Delaware River at Delaware Memorial Bridge.

SPECIFIC CONDUCTANCE OBSERVATIONS

Observations of specific conductance of the river water were made during the tidal-cycle measurements at the Burlington-Bristol Bridge on August 16, 17, 24, 1956, and at the Delaware Memorial Bridge on August 21, 1957. At the Delaware Memorial Bridge a clearly defined variation in specific conductance was shown by the continuous con-

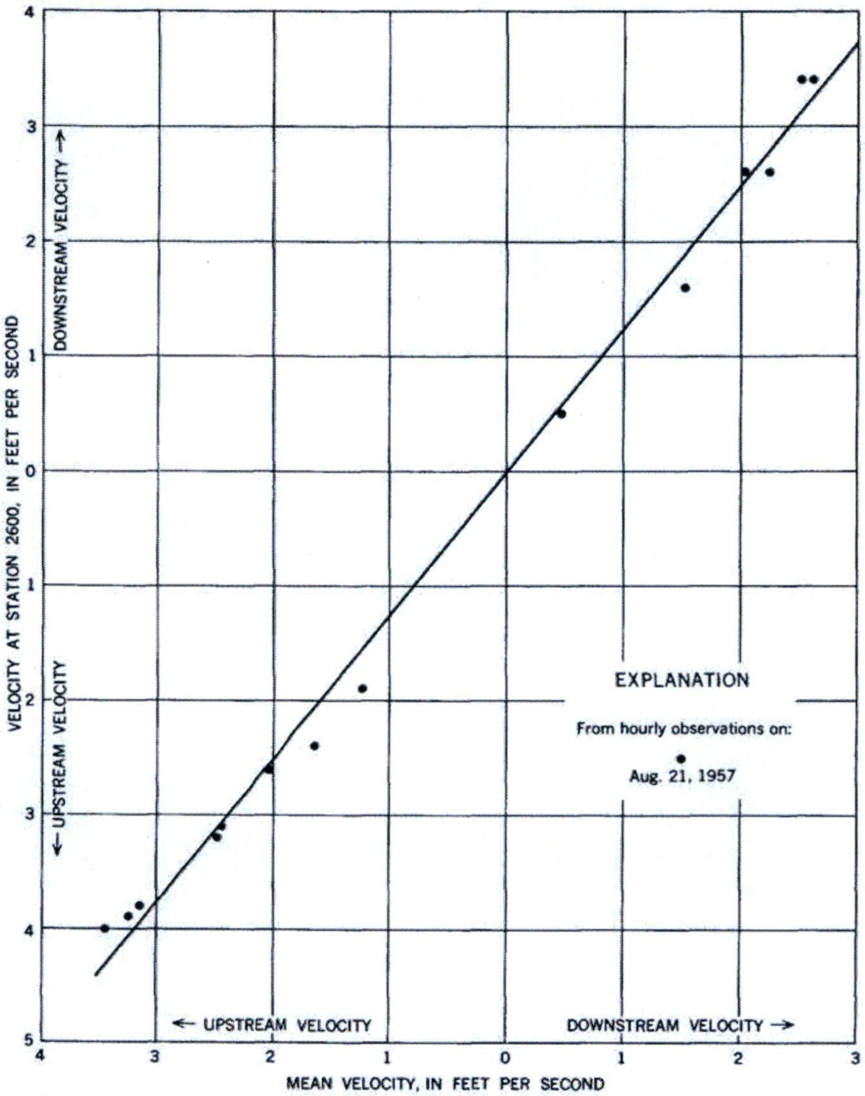

FIGURE 11.—Relation of mean velocity and velocity at station 2600 of Delaware River at Delaware Memorial Bridge.

ductance recorder located near the tower pier on the Delaware side of the main channel. To investigate the relationship between the mean specific conductance in the river cross section and the specific conductance at the site of the continuous recorder, water samples were taken at various points and times during the day and specific conductance was measured. Samples were taken about four times an hour at the index meter at 0.6 depth. At four times during the day,

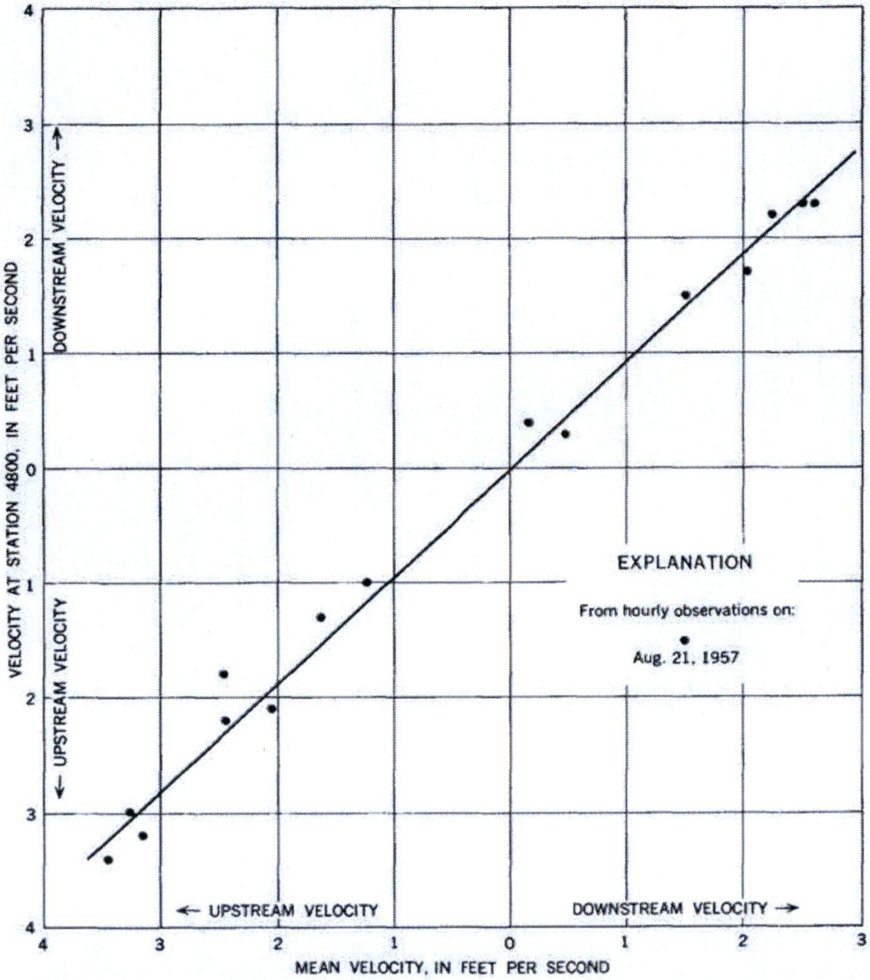

FIGURE 12.—Relation of mean velocity and velocity at station 4800 of Delaware River at Delaware Memorial Bridge.

water samples were taken at the top and bottom at five other designated spots in the cross section. Figure 13 shows the plotting of the specific conductance for all these observations. Where samples were taken at top and bottom, the mean of the two values was plotted.

Because of the limited number of observations, no attempt was made to compute an exact weighted mean specific conductance in the river for any time. The observations of specific conductance taken at 0.6 depth at the index meter seemed to average in a general way the spot samples taken across the cross section, however, and a line connecting the individual observations at 0.6 depth at the index meter

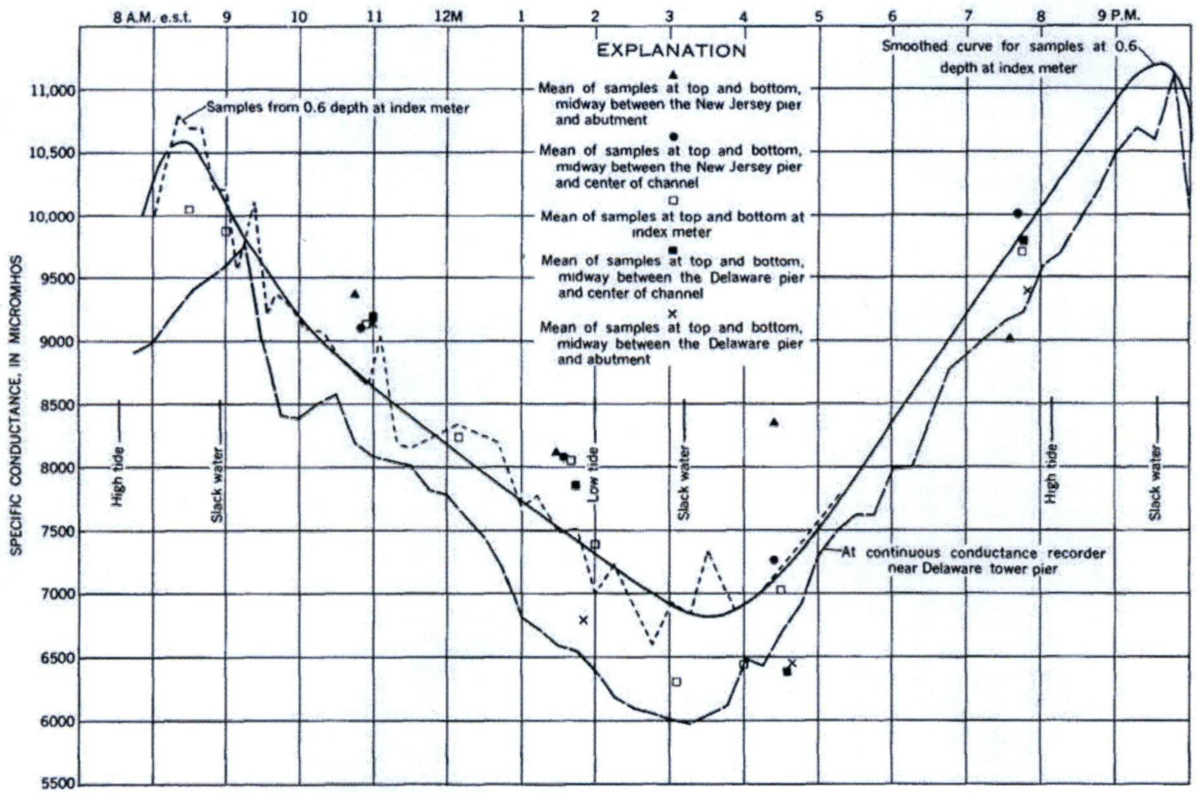

FIGURE 13.—Specific conductance hydrographs of Delaware River at Delaware Memorial Bridge, August 21, 1957.

was roughly parallel to the line of variation of specific conductance obtained from the continuous conductance recorder. A smoothed curve for the samples at 0.6 depth at the index meter was drawn as shown in figure 13 and considered representative of the variation in specific conductance in the river cross section for the time of the observations.

A comparison of the curve of representative specific conductance, as shown in figure 13, with the variation of gage height at the Delaware Memorial Bridge, as shown in figure 7, demonstrates the general relation that as the tide comes in, the specific conductance increases, and as the tide goes out, the specific conductance decreases. The actual values of the specific conductance, however, depend upon the antecedent conditions of river discharge and water level in the bay.

It was shown by Durfor and Keighton [1] that above a chloride concentration of 60 ppm (parts per million) in the Delaware River tidal estuary, the relation between the chloride concentration and electrical conductivity is approximately a straight line when plotted on a logarithmic scale. Thus, the record of the variation of specific conductance through the tidal cycles can be used as a measure of the variation of chloride concentration, which in high concentration indicates primarily the presence of sea water. By comparison of the specific conductance of the water at the Delaware Memorial Bridge with that of fresh water entering the tidal estuary and the specific conductance of sea water, it is possible to compute by a simple proportion the fraction of the water passing the Delaware Memorial Bridge that had its origin from fresh-water sources and the fraction that had its origin from oceanic sources. It seems that additional investigation of the relations mentioned above would be a desirable contribution to the study of tidal estuaries.

The results of the observations of specific conductance for the measurements at the Burlington-Bristol Bridge are not recorded in this report. The specific conductance determinations varied between 185 and 210 micromhos, approximately the same values as obtained for samples of fresh water taken at the head of tide at Trenton. Obviously, the variation in values of specific conductance at the Burlington-Bristol Bridge was not directly related to tidal action, and it was not possible to distinguish the direction of flow at any time from specific conductance determinations at this location.

[1] Durfor, C. N., and Keighton, W. B., 1954, Chemical characteristics of Delaware River water, Trenton, New Jersey, to Marcus Hook, Pennsylvania: U.S. Geol. Survey Water-Supply Paper 1262, fig. 12.

CONCLUSIONS

Velocity hydrographs were constructed for all designated stations in the cross sections so that the velocity at any station could be determined for any time during the tidal-cycle measurements. These figures of velocity, in conjunction with soundings, were used to compute river flow during the measurements.

In all five measurements, the maximum upstream velocity at the index meter was greater than the maximum downstream velocity. This is illustrated in figures 6 and 7. For the four measurements at the Burlington-Bristol Bridge, the downstream flow was sustained for a longer period than the upstream flow. This was not true for the measurement at the Delaware Memorial Bridge, probably because the evening high tide was 1.4 feet higher than the morning high tide and resulted in a comparatively large upstream flow.

The maximum rates of tidal flow at the Delaware Memorial Bridge dwarfed the fresh-water discharge of the Delaware River entering the tidal section of the river. On the day of the measurement at the Delaware Memorial Bridge the maximum rate of downstream flow was almost 400,000 cfs, and the maximum rate of upstream flow was almost 600,000 cfs. The same day, the mean discharge of the Delaware River at Trenton was only 1,650 cfs. The maximum discharge ever recorded at Trenton was 329,000 cfs on August 20, 1955, a lower rate of flow than an ordinary rate of tidal flow at the Delaware Memorial Bridge.

A measure of distance of water travel during the tidal cycles was obtained by integrating the areas under the velocity hydrographs at the index meters. The length of these filaments of water passing the index meters ranged from 28,700 to 48,100 feet at the Burlington-Bristol Bridge and from 49,200 to 62,600 feet at the Delaware Memorial Bridge. Additional investigations might develop the relationships between these measures of water travel and some aspects of the actual water travel. If valid correlations could be made, the simplicity of determining water travel by measuring at one spot with a current meter would make the method useful.

All five tidal-cycle measurements were made at times when the fresh-water discharge at Trenton was comparatively low. To determine the effects of higher fresh-water discharge on the tidal flow, it would be desirable to make additional measurements at times of medium and high river discharge.

The combinations of the ranges of tides causing tidal flow are limitless. Of the five measurements made, three were made from high tide to high tide and two from low tide to low tide. On two occasions the height of the evening tide was within one-half foot of the height of the morning tide; on two occasions the height of the evening tide was about one foot lower than the morning tide; and for the measurement at the Delaware Memorial Bridge the evening tide was 1.4 feet higher than the morning tide. Other tidal ranges could be selected for future investigations that would add to this variety.

Although the variations in river flow during the five measurements were well defined, it was concluded that reliable figures of net downstream discharge could not be obtained by subtracting the total upstream flow from the total downstream flow and correcting for changes in storage. It follows that this procedure could not be used satisfactorily to detect ground-water inflow. Work could be done to improve the accuracy of the flow determinations and to refine the figures of storage corrections to obtain more dependable net discharge figures, but a realistic appraisal of the probable results should be made before any work is started.

The correlations showed that at some stations away from the main ship channel the mean velocity in the vertical correlated quite well with the mean velocity in the river. This result indicated that a permanent flowmeter might be installed at one of those stations to provide a continuous record of velocity at that point, which in turn would provide the mean velocity in the river through use of the correlation curve. Before any flowmeter is installed for this purpose, however, additional investigations should be made to determine whether velocity at a fixed point in the vertical would correlate satisfactorily with the mean velocity in the river cross section. If the answer to this question should prove to be affirmative, it would be entirely possible to compute a continuous record of the tidal flow with records from a flowmeter and a continuous water-stage recorder as the base data.

Observations of specific conductance at the Burlington-Bristol Bridge showed no significant variation during the tidal cycles studied. At the Delaware Memorial Bridge, however, the observations showed a pronounced variation in specific conductance. It was observed that as the tide came in the specific conductance increased and as the tide went out it decreased. The variation in specific conductance was a measure of the salinity caused by the movement of ocean water upstream. Thus the specific conductance observations could be used to compute the fraction of the water passing the Delaware Memorial Bridge that had its origin from oceanic sources.

TABLE 1.—*Computations of hourly flow of Delaware River at Burlington-Bristol Bridge and Delaware Memorial Bridge, August 1955–57*

Time (e.s.t.)	Gage height (ft)	Area (sq ft)	Downstream		Upstream	
			Mean velocity (fps)	Flow (cfs)	Mean velocity (fps)	Flow (cfs)
Burlington-Bristol Bridge, August 9, 1955						
6:44 a.m.	6.7	32,600	0	0	0	0
7:00	6.5	32,300	.51	16,600		
8:00	5.6	31,200	2.02	63,000		
9:00	4.5	30,000	2.15	64,300		
10:00	3.4	28,600	1.66	47,500		
11:00	2.3	27,300	1.57	42,900		
1:00 p.m.	.4	25,100	1.23	31,000		
1:52	.2	24,900	0	0	0	0
2:00	.4	25,100			.86	21,600
2:30	1.8	26,700			2.18	58,300
3:00	2.6	27,600			2.71	75,000
4:00	4.0	29,300			2.33	68,300
4:30	4.8	30,200			2.03	61,300
5:00	5.6	31,200			1.99	62,100
6:00	6.7	32,600			1.48	48,400
7:00	7.1	33,100			.55	18,200
7:26 p.m.	6.9	32,900	0	0	0	0

Integrated length of water travel past index current meter during tide cycle:
Downstream............ feet 41,000
Upstream............ do 41,000
Integrated volume of water movement during tide cycle:
Downstream............ million cubic feet 1,090
Upstream............ do 1,040

Time (e.s.t.)	Gage height (ft)	Area (sq ft)	Downstream mean velocity (fps)	Downstream flow (cfs)	Upstream mean velocity (fps)	Upstream flow (cfs)
Burlington-Bristol Bridge, August 16, 1956						
6:36 a.m.	0.7	26,400	0	0	0	0
7:00	1.3	27,100			1.23	33,300
8:00	2.5	28,500			2.31	65,900
9:00	4.0	30,300			1.86	56,500
10:00	5.1	31,700			1.41	44,600
11:00	5.6	32,300			.62	20,100
11:30	5.5	32,200	0	0	0	0
12:00 m.	5.2	31,800	.92	29,200		
1:00 p.m.	4.3	30,700	2.02	62,000		
3:00	2.2	28,200	1.64	46,200		
5:00	.2	25,900	1.38	35,700		
6:00	−.4	25,200	.87	22,000		
6:28 p.m.	−.1	25,500	0	0	0	0

Integrated length of water travel past index current meter during tide cycle:
Downstream............feet.. 39,900
Upstream............do... 29,100
Integrated volume of water movement during tide cycle:
Downstream............million cubic feet.. 1,030
Upstream............do.. 766

TABLE 1.—*Computations of hourly flow of Delaware River at Burlington-Bristol Bridge and Delaware Memorial Bridge, August 1955–57*—Continued

Time (e.s.t.)	Gage height (ft)	Area (sq ft)	Downstream		Upstream	
			Mean velocity (fps)	Flow (cfs)	Mean velocity (fps)	Flow (cfs)
Burlington-Bristol Bridge, August 17, 1956						
7:00 a.m	0	25,800	1.06	27,300		
7:32	.1	25,900	0	0	0	0
8:00	1.3	27,400			1.46	40,100
9:00	2.5	28,700			2.31	66,200
10:00	4.0	30,500			1.96	59,700
11:00	5.1	31,900			1.45	46,100
12:00 m	5.7	32,600			.56	18,200
12:24 p.m	5.8	32,800	0	0	0	0
1:00	5.3	32,100	1.06	34,200		
2:00	4.4	31,000	1.93	60,000		
3:00	3.2	29,500	1.81	53,500		
4:00	2.1	28,200	1.63	45,900		
6:00	.2	26,000	1.29	33,500		
7:00	-.4	25,400	.60	15,200		
7:15 p.m.	0	25,800	0	0	0	0

Integrated length of water travel past index current meter during tide cycle:
Downstream .... feet .. 40,100
Upstream .... do 28,700
Integrated volume of water movement during tide cycle:
Downstream .... million cubic feet .. 993
Upstream .... do 814

Time (e.s.t.)	Gage height (ft)	Area (sq ft)	Downstream Mean velocity (fps)	Downstream Flow (cfs)	Upstream Mean velocity (fps)	Upstream Flow (cfs)
Burlington-Bristol Bridge, August 24, 1956						
4:46 a.m.	7.2	34,500	0	0	0	0
5:00	7.0	34,200	.68	23,200		
6:00	6.0	33,000	2.02	66,500		
7:00	4.9	31,600	2.09	65,800		
9:00	2.8	29,000	1.61	46,600		
11:00	1.0	26,900	1.36	36,600		
12:00 m	.7	26,600	.15	3,980		
12:03 p.m.	.9	26,800	0	0	0	0
1:00	2.6	28,700			2.18	62,700
2:00	4.0	30,500			2.31	70,200
3:00	5.5	32,300			1.67	54,200
4:00	6.2	33,200			1.00	33,200
4:42	6.1	33,000	0	0	0	0
5:00 p.m.	5.8	32,700	.79	25,900		

Integrated length of water travel past index current meter during tide cycle:
Downstream .... feet .. 48,100
Upstream .... do 29,300
Integrated volume of water movement during tide cycle:
Downstream .... million cubic feet .. 1,250
Upstream .... do .. 797

TABLE 1.—*Computations of hourly flow of Delaware River at Burlington-Bristol Bridge and Delaware Memorial Bridge, August 1955–57—Continued*

Time (e.s.t.)	Gage height (ft)	Area (sq ft)	Downstream		Upstream	
			Mean velocity (fps)	Flow (cfs)	Mean velocity (fps)	Flow (cfs)
Delaware Memorial Bridge, August 21, 1957						
7:00 a.m.	4.8	171,000			2.48	424,000
8:00	4.8	171,000			1.63	280,000
8:56	4.2	168,000	0	0	0	0
9:00	4.1	167,000	.17	28,000		
10:00	3.0	161,000	1.52	245,000		
11:00	2.1	156,000	2.24	348,000		
12:00 m.	1.3	151,000	2.61	394,000		
1:00 p.m.	.7	148,000	2.51	370,000		
2:00	.3	145,000	2.03	296,000		
3:00	.7	148,000	.49	72,100		
3:13	1.1	150,000	0	0	0	0
4:00	2.6	158,000			2.03	322,000
5:00	3.8	166,000			3.16	523,000
6:00	5.0	173,000			3.44	594,000
7:00	5.8	177,000			3.26	578,000
8:00	6.2	180,000			2.44	418,000
9:00	6.0	178,000			1.23	220,000
9:37 p.m.	5.5	175,000	0	0	0	0

Integrated length of water travel past index current meter during tide cycle:
Downstream........feet.. 49,200
Upstream........do.... 62,600
Integrated volume of water movement during tide cycle:
Downstream........million cubic feet.. 6,390
Upstream........do.... 9,420

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